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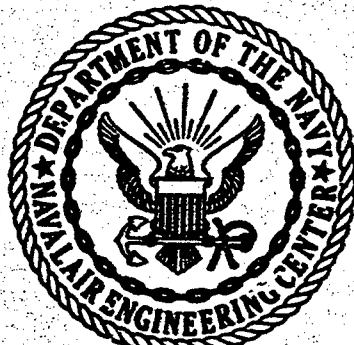
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ANALYSIS OF GAS TURBINE ENGINE FAILURE MODES



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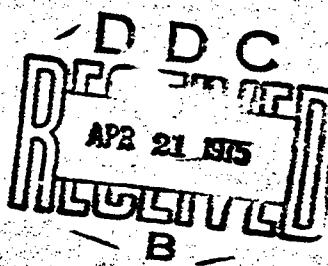


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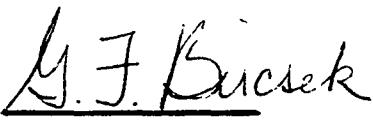
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ANALYSIS OF GAS TURBINE

ENGINE FAILURE MODES

PREPARED BY

G. F. BUCSEK



APPROVED BY

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13. ABSTRACT This report presents the findings of a thorough investigation of gas turbine engine failure modes and causal factors over a six-month period. Specific problem areas and opportunities for improvement of diagnostic hardware and techniques are identified. Recommendations for solution are developed based on the data base established during the investigation and documented in the appendices.		

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ABSTRACT

This report contains the findings of an in-depth study of Navy aviation gas turbine engine failure modes and causal factors. Specific areas of potential engine malfunction are identified including determination of the associated diagnostic techniques and hardware. An extensive compilation of engine malfunction is presented as a basis for long-range projections of anticipated engine performance with respect to potential areas of failure. This, in turn, has made possible certain recommendations for enhancing Navy gas turbine engine service reliability, with a view to forestalling to the optimum extent catastrophic engine failure.

1.0 INTRODUCTION

The susceptibility to malfunction in aviation gas turbine engines is more pronounced in Navy airframes than in their commercial counterparts. This is due to several factors, the more obvious being the relatively more severe and extreme ranges of Navy operational demands placed upon the engines, plus the continuing shortage of skilled maintenance and overhaul personnel available to fleet units and associated shore activities.

In recognition of these factors, an in-depth study of Navy aviation gas turbine engines was conducted over a six-month period. The primary objective of this effort was to analyze selected gas turbine systems with a view to identifying specific failure modes, their frequency, and their causal factors.

Secondary objectives of the study were to:

a. Develop a composite data base considered representative of Navy aviation gas turbine problems;

b. Identify specific gas turbine system problems; i.e., the most prevalent failures; and

c. Identify difficulties associated with gas turbine system fault isolation and detection through use of external instrumentation and diagnostic techniques, and identify areas where improvements could be effected in such techniques or equipment.

Data for this study was compiled from the operating and maintenance histories of six gas turbine engine types, involving a total of 290 such engines considered representative of current and future Navy inventories. The bulk of the input was derived from seven naval aircraft types supported by four Naval Air Stations (Oceana and Norfolk, Virginia; and Jacksonville and Cecil Field, Florida). This data was supplemented by discussions with personnel engaged in a SOAP (Spectrometric Oil Analysis Program) at the Norfolk NARF (Naval Air Rework Facility) Laboratory.

It is noted that no meaningful correlation can be established between Navy and commercial practice with respect to gas turbine engine failure. The relatively severe missions and generally adverse ambient conditions under which naval aircraft must function, coupled with the average 12-year experience of the civilian maintenance crew versus the average 2-year experience of its Navy counterpart militate against such useful comparison of apparatus and techniques.

2.0 SUMMARY OF STUDY PROCEDURES AND RESULTS

2.1 Procedures. Failure modes of the following gas turbine engines were studied: J-52, J-79, T-56, T-58, TF-30, and TF-41. Engine condition diagnostic test equipment external to the airframe included the JET CAL analyzer, TRIM TESTER, JET ENGINE TEST FACILITIES (cells and stands) and the SOAP. All of these are presently in use at the O (Organizational), I (Intermediate), and Depot levels of aircraft maintenance. The ADMRL (Application Data, Material Readiness List) applicable to the selected airframes and engines was the authorizing document for such non-integrated test equipment for both O and I level activities.

In the initial stages of the study, a thoroughly experienced team comprised of aircraft maintenance engineers and technical data analysts developed detailed data recording sheets, questionnaire and interview forms for use during on-site surveys. Visits to the aforementioned designated AIMD (Aircraft Intermediate Maintenance Departments) were conducted by members of this study team. Those thus interviewed included supervisors and mechanics working in the Power Plant, Quality Assurance, and Administration Divisions/Work Centers. Through such team efforts, relevant 3-M (Maintenance and Material Management) data was extracted, merged and analyzed in order to develop a workable composite data base for the study.

2.2 Results. Implementation of the foregoing procedures yielded the following determinations:

a. Four major gas turbine engine failure modes indicated by 3-M data are: FOD (Foreign Object Damage), excessive thermal stress, internal leakage of oil due to faulty seals, and failure attributed to excessive vibration. Under present conditions, FOD inspection procedures necessitate personnel entry into the intake duct if the engine in question is located deep within the airframe. This is not only difficult but is even hazardous to perform unless elaborate safety precautions are observed.

b. Currently, aircraft instrumentation and associated sensors for precise time/temperature measurement are inadequate to meet desirable diagnostic technique requirements. This constitutes an area for improvement effort.

c. False (needless) removal of suspect engines from airframes does not constitute a significant problem insofar as diagnostic techniques are involved.

d. Other than the SOAP there is only a limited capability within the Navy to predict gas turbine engine performance and life expectancy in service. The SOAP, however, employs a non-integrated diagnostic technique that shows infinitely more potential than is currently being realized.

e. Utilization of other non-integrated measures varies in quality and reliability. To cite a few examples, JETF (Jet Engine Test Facilities) or test cells and stands, except for those handling the TF-41 engines, are deemed adequate. Similarly, the JET CAL analyzers are considered adequate per se, although their actual effectiveness varies widely in relation to the training, experience and discipline of the user activity. In the main, the TRIM TESTERS have proven to be even less reliable than the JET CALS, chiefly attributed to lack of confidence on the part of their users. As a result, TRIM TESTERS have relatively low utilization.

f. Gas turbine engines generate sufficient data to permit adequate condition monitoring. The shortcomings lie in the readout and analysis of the generated data.

3.0 CONCLUSIONS

The following conclusions resulted from the study:

- a. Predominant causes of naval aviation gas turbine engine failure are: operational environment, airframe design that results in restricted access to the power plant, relatively high power plant rating as compared with commercial applications, lack of adequate installed sensors and diagnostic instrumentation, and induced malfunctions due to inadequate maintenance personnel skills and experience.
- b. There is a definite requirement to develop and provide to operating activities an optical FOD detector, thus precluding the necessity of personnel access into the engine intake duct.
- c. An effective non-integrated gas turbine diagnostic/prognostic system is within the state-of-the art; however, development of such a system would require new support equipment, expanded engine data reporting and dedicated management for a gas turbine engine condition maintenance program.
- d. The training of JET CAL/TRIM TESTER operators and the discipline of the user maintenance activities is adequate. The utilization of these devices should receive close attention prior to procurement of additional equipment or to consideration of an ECP (Engineering Change Proposal).
- e. The SOAP has marked potential of serving as the basis of an engine condition prognostic system.
- f. An improved design of vibration analyzer equipment is needed for JETF application to the TF-41 engine.
- g. Integrated precision time/temperature measurement sensors are required to provide advance indications of conditions leading to engine failure.
- h. Future airframe design should provide for improved accessibility to the power plant.

4.0 RECOMMENDATIONS

The following recommendations are made as a result of the study:

- a. Develop and provide to operating activities an optical FOD detector that will not require personnel entry into engine intake ducts for inspection purposes.
- b. By prototyping a gas turbine engine condition maintenance program, determine the feasibility of an expanded diagnostic/prognostic concept.
- c. Conduct an engineering investigation of the prototype vibration analyzer presently installed on the TF-41 JETF, with a view to providing that unit to appropriate AIMDs or to develop an improved analyzer capable of simultaneous display of vibration data.
- d. Provide oil analysis spectrometers to all shore-based AIMDs, thereby improving real-time reporting and ensuring continuity of record transfer.
- e. Expedite development and application of precision integrated time/temperature measurement sensors.
- f. Expedite development and application of integrated vibration sensors.
- g. During the design and development stages of airframe and power plant, provide for effective maintainability through enhanced access to engine and components; this is to be done on equal level of importance and criticality of aircraft performance, weight, safety and reliability.

5.0 TABLE OF CONTENTS

	PAGE NO.
ABSTRACT	
1.0 INTRODUCTION	i
2.0 SUMMARY OF PROCEDURES AND RESULTS	ii
2.1 Procedures	
2.2 Results	
3.0 CONCLUSIONS	iv
4.0 RECOMMENDATIONS	v
5.0 TABLE OF CONTENTS	vi
6.0 GLOSSARY	viii
7.0 REPORT TEXT	1
7.1 Introduction	1
7.2 Study Scope	1
7.3 Data Requirements	1
7.4 Analysis of Failure Data	2
7.4.1 General	2
7.4.2 Failure Data	3
7.4.3 When Discovered Data	4
7.4.4 Malfunction Data	5
7.4.5 Action Taken Data	6
7.5 Failure Modes	6
7.5.1 Most Prevalent Failures	6
7.5.2 FOD	6
7.5.3 Thermal Stress	7
7.5.4 Oil Leakage and Excessive Vibration	7
7.6 Failure Causal Factors	8
7.6.1 General	8
7.6.2 Operational Environment	8
7.6.3 Airframe Design and Power Plant Accessibility	9
7.6.4 Power Plant Rating	9
7.6.5 Sensors and Instrumentation	10
7.6.6 Maintenance Personnel Skill and Experience	10
7.7 Non-Integrated Engine Diagnostic Test Equipment	11
7.7.1 Definition	11
7.7.2 Current Status	11
7.7.3 JET CAL Analyzer	12
7.7.4 TRIM TESTER	12
7.7.5 JETFs	12
7.7.6 SOAP	12

5.0 TABLE OF CONTENTS (Cont'd)

	PAGE NO.
7.7.7 Optical FOD Detection	13
7.8 Diagnostic System	14
7.8.1 Elements of a Diagnostic System	14
7.9 Summary of Non-Integrated Diagnostic Problems	17
7.9.1 Engine Performance	17
APPENDICES	
A Engine Characteristics and Aircraft Application	A-1
B Composite Engine Failure Data	B-1
C Composite Engine and High Failure Component Data	C-1
D J-52 Engine and High Failure Component Data	D-1
E J-79 Engine and High Failure Component Data	E-1
F T-56 Engine and High Failure Component Data	F-1
G T-58 Engine and High Failure Component Data	G-1
H TF-30 Engine and High Failure Component Data	H-1
I TF-41 Engine and High Failure Component Data	I-1
J Typical Aircraft and Test Cell Instrumentation	J-1

6.0 GLOSSARY

ADMRL	Application Data, Material Readiness List
AIMD	Aircraft Intermediate Maintenance Department
BCM	Beyond Capability of Maintenance
CER	Complete Engine Repair
CGSE	Common Ground Support Equipment
CSD	Constant Speed Drive
CVA	Attack Carrier
DIR	Disassembly Inspection Report
ECP	Engineering Change Proposal
EGT	Exhaust Gas Temperature
FOD	Foreign Object Damage
I	Intermediate Level of Maintenance
JETF	Jet Engine Test Facility
MDCS	Maintenance Data Collection System
MRC	Maintenance Requirement Card
MTBF	Mean Time Between Failure
NARF	Naval Air Rework Facility
NAS	Naval Air Station
O	Organizational Level of Maintenance
PAR	Progressive Aircraft Rework
PM	Preventive Maintenance
RDT&E	Research, Development, Test and Evaluation
RFI	Ready for Issue

6.0 GLOSSARY (Cont'd)

R&D	Research and Development
SOAP	Spectrometric Oil Analysis Program
TAT	Turn Around Time
T/M/S	Type, Model, Series of Aircraft
WC	Work Center
WUC	Work Unit Code
3-M	Maintenance and Material Management

7.0 REPORT TEXT

7.1 Introduction. The Naval Air Engineering Center was tasked with conducting an in-depth study of gas turbine engines with a view to determining improved techniques and equipment for detecting jet engine performance degradation, ascertaining causal factors of such degradation, predicting maintenance requirements, and establishing repair/rework milestones. The intent was to forestall in-flight catastrophic failures.

To effectively pursue such a study required the precise determination of the most prevalent types of jet engine failures and their associated causal factors. A composite data base was therefore compiled upon which future integrated and non-integrated diagnostic/prognostic equipment and techniques could be developed to meet this mandatory requirement.

7.2 Study Scope. The study was confined to the following gas turbine engines and Type, Model and Series aircraft:

<u>Engine</u>	<u>Aircraft</u>
J-52	A-4, A-6
J-79	F-4
T-56	E-2, P-3
T-58	H-2, H-3, H-46
TF-30	A-7
TF-41	A-7E

Activities concerned with the studied engines and aircraft included NAS Oceana and NAS Norfolk, Virginia; NAS Jacksonville and NAS Cecil Field, Florida. At those activities, AIMDs responsible for CER (Complete Engine Repair) were visited for consultation with respect to the respective engines.

As a result of consultations with such cognizant shore activity and fleet personnel, power plant system problems and difficulties encountered in employing current non-integrated (external to airframe) diagnostic equipment, areas were identified showing promise of improvement in diagnostic techniques and equipment. Such areas were documented in the course of the study.

7.3 Data Requirements. Task data requirements were determined and identified on the basis of past maintenance experience and work study methodology. These requirements, segregated into primary and secondary objectives, were studies in detail and itemized in terms of problem definition. Data input requirements were subsequently refined as the study progressed.

Data recording forms were then developed to facilitate comprehensive extraction and segregation of jet engines and their component data for the selected gas turbine engines as furnished by the on-site MDCS (Maintenance Data Collection System). Since AIMDs are required to retain the last six months of engine repair data, a data base extending from October 1973 through March 1974 was selected as the study base. Elements investigated on that basis included the WUC (Work Unit Code) employed to identify the studied system, sub-system, assembly or component of the selected gas turbine engines. The WDC (When Discovered Code) used in the study represents when the need for maintenance was detected; the MDC (Malfunction Description Code) related to equipment faults; and the ATC (Action Taken Code) denotes what maintenance action was involved. Maintenance reports and associated data thus developed by the Navy's 3-M System provided the bulk of the input for the failure mode analysis.

A questionnaire was then developed to aid field team members in their interviews with fleet and shore station personnel. These forms also ensured that each category of desired information was fully explored and exploited. Such categories included the methods of documenting specific maintenance actions, inspections on a calendar basis, engine oil analysis procedures, the inventory and utilization of non-integrated engine diagnostic equipment, aircraft and jet engine test facility instrumentation and its utilization, pertinent test/troubleshooting procedures, and problem areas holding potential for improvement in fault detection and isolation.

Data investigated as an integral part of this study are discussed in detail in subsequent paragraphs and are appropriately listed in the composite data base provided in Appendices A through J.

7.4 Analysis of Failure Data.

7.4.1 General. The gas turbine engines selected for this study were deemed representative of current and contemplated Navy inventories. Details of the engine characteristics are provided in Appendix A.

Data elements from the 3-M MDCS analyzed included the WUC, WDC, MDC, and ATC. For example; WDC alphabetic code A represents Before-Flight-Abort-Aircrew, WDC code M relates to Calendar/Calendar ODD/Major/Phased Inspection. By selective grouping of the data element discrete codes it could be determined if Flight Crew, Inspections, Maintenance or Test Cell operation initially discovered the functional discrepancy. The MDC served to indicate the reported fault, and provided clear indication of specific engine problem areas. The ATC notes what maintenance was undertaken, including No Defect Encountered, Repair, or BCM (Beyond Capability of Maintenance) action at the Intermediate maintenance level.

All data acquired from the MDCS were verified and amplified in the course of field team interviews with cognizant fleet personnel supplemented by research of pertinent technical publications.

7.4.2 Failure Data. In all appendices to this report, the "Six Months Data Sample" column lists the number of engine samples processed by the CER activities. Therefore, discrete malfunction codes (e.g., No Defect; No Defect-Removed for Modification, No Defect-Removed due to reaching maximum scheduled operating time, etc.) are to be disregarded in determining what constitutes valid failure data. A tabulation of the engines qualifying for evaluation is as follows:

<u>ENGINE</u>	<u>NUMBER OF ENGINES PROCESSED</u>	<u>NUMBER OF ENGINE FAILURES</u>	<u>NUMBER OF NO-DEFECT MALFUNCTION CODES</u>
J-52	44	40	4
J-79	89	69	20
T-56	23	18	5
T-58	37	32	5
TF-30	28	23	5
TF-41	<u>69</u>	<u>58</u>	<u>11</u>
Totals	290	240	50

In the tabulation, component failures are given the same weight as engine failure data. In addition, before a component was considered to have a high failure rate, and listed as such in the appendices, a minimum of five failures had to be documented for such components. For example, the front compressor case in the failed J-52 engine had only two discrepancies documented. Although in each instance the failures were due to FOD, these particular engines were omitted from the studied data because less than five occurrences had been documented. Components having five or more documented maintenance actions are therefore listed as items processed. As a result, the No-Defect Malfunction Codes are to be deleted, as in the following:

<u>ENGINE</u>	<u>NUMBER OF COMPONENTS PROCESSED</u>	<u>NUMBER OF COMPONENT FAILURES</u>	<u>NUMBER OF NO-DEFECT MALFUNCTION CODES</u>
J-52	229	226	3
J-79	304	298	6
T-56	193	187	6
T-58	166	135	31
TF-30	111	109	2
TF-41	<u>2,472</u>	<u>2,471</u>	<u>1</u>
Totals	3,475	3,426	49

It is to be noted that the most important No-Defect diagnostic code applies where an operational discrepancy has been reported, the item in question was removed from the airframe and processed for repair, but no actual defect was found in the course of the check-out procedure. This means that an item actually RFI (Ready For Issue) had been incorrectly reported as having failed in operation. On the basis of No-Defect data extracted for the engines processed in the study, only 10 of the 290 units (3 percent) appeared in this category. It is evident, therefore, that false removal of engines does not constitute a serious maintenance problem. Appendix B amplified this finding.

Of the 3,475 components processed, only five false removals were documented. It is to be noted, however, that some of these components proved to be BCM at the I level yet were subsequently found defect-free at the Depot level. To illustrate, other than on JETF, as part of a complete engine functional check, the I level does not possess the capability of evaluating fuel controls. Consequently, although the No-Defect Code is susceptible to understatement, it should not be accorded undue significance. Appendices C through I provide amplification on this point.

7.4.3 When Discovered Data. As noted previously, the WDC structure identifies when and/or by whom an engine performance discrepancy was detected. If the discrepancy was discovered in the course of flight crew preflight checks, inflight, post-flight or at the pilot's weekly aircraft inspection, then the Flight Crew codes are used. The Inspections code related to ground crew and maintenance personnel performing their daily, special, calendar, conditional or quality assurance inspections, and also included oil analysis recommendation. The term "During Maintenance" refers to discrepancies noted when the unit was subjected to in-shop repair and/or disassembly for maintenance. For example, if a J-52 engine was reported as FOD via a daily inspection performed at the O level, when the engine was subsequently disassembled by Work Center personnel at the I level, a cracked inlet case may have been found in addition to FOD to the front and rear compressor rotors. In this example, the When Discovered Codes would be as follows:

<u>WHEN DISCOVERED</u>	<u>ENGINE/COMPONENT</u>
Inspections	J-52 Engine
During Maintenance	Compressor Inlet Case
During Maintenance	Front Compressor Rotor
During Maintenance	Rear Compressor Rotor

The foregoing example demonstrates that as the depth of maintenance increases, so the number of discrepancies encountered and reported may increase. The number/percentage data attributed to the

During Maintenance phase would thus have increased significance. Extraction of Appendices B and C data further illustrate this point in When Discovered documentation, as follows:

<u>ITEMS PROCESSED</u>		<u>FLIGHT CREW</u>	<u>INSPECTIONS</u>	<u>DURING MAINTENANCE</u>	<u>IN TEST CELL</u>
All Engines	#	156	109	19	06
	%	54	38	06	02
All Engines and Components	#	357	737	2,573	98
	%	09	20	68	03

Component accessibility for visual inspection, plus the level of instrumentation available to the flight crew during flight operations provide a certain measure of diagnostic capability for detecting basic forms of engine malfunction. However, such measures do not provide sufficient in-depth capability of detecting component failure. Although inspection crews enjoy greater accessibility due to pulling the engine from the airframe to facilitate PM (Preventive Maintenance) inspection, the ensuing in-shop and/or engine dismantling for maintenance ensures greatly enhanced visual inspections.

The high percentage of component discrepancies uncovered by maintenance crews in the course of correcting a different reported discrepancy clearly demonstrates the requirement for enhanced accessibility during inspections: primarily for PM by inspection crews, and secondarily for flight crews.

7.4.4 Malfunction Data. With the exception of the No-Defect codes discussed in subsection 7.4.2, the MDCs are assigned to indicate the trouble or cause of the trouble. It is to be remembered that No-Defect codes do not represent valid failures, but serve to indicate false removal of engines from the airframe, attainment of maximum operating time (which is significant in lieu of on-condition maintenance), or to designate other categories of non-failure removal. A complete listing of Malfunction Description Codes is contained in OPNAV 4790.2A, Volume III, Appendix E, whereas Appendices B through I to this report contain only alphabetic description of the codes documented against all of the studied engines and components. For example, overspeed was reported as a source of J-52 malfunction, but this factor proved unique in the sampled data. However, overspeed remains listed throughout all of the engine data sheets to permit analysis of omission as well as commission, i.e., overspeed remains at least as a causal possibility.

Malfunction Description Codes are the primary source of propulsion system failure mode and causal factor data, therefore, they constitute the bulk of the composite data base relevant to this study.

7.4.5 Action Taken Data. The Action Taken Codes are assigned to indicate the ultimate disposition of items processed by the maintenance activity. (The No-Defect and Repaired Actions are self-explanatory.) The BCM code indicates that a theoretically repairable item proved irreparable when it was administratively or technically screened by the AIMD. Nine discrete reason codes are available for the action taken factor, e.g., BCM-1 translates as Repair Not Authorized; BCM-4 signifies Lack of Parts; BCM-9 signifies Condemned; etc. It is of interest that 99 percent of all BCM codes were either 1 or 9, although all are shown grouped in the several appendices to this report.

7.5 Failure Modes.

7.5.1 Most Prevalent Failures. During the six-month sample period 290 gas turbine engines were documented as removed from airframes. Since non-failures accounted for 50 of these removals, failure modes and causal factors are assignable to only 240 of these units. Thus, a documented failure breakdown by engine type is as follows:

<u>ENGINE</u>	<u>FAILURES</u>
J-52	40
J-79	69
T-56	18
T-58	32
TF-30	23
TF-41	<u>58</u>
Total	240

<u>FAILURE MODE</u>	<u>NUMBER</u>
FOD	80
Thermal Stress	73
Oil Leakage	22
Excessive Vibration	10
Unclassified(1)	<u>55</u>
Total	240

(1) Unclassified is defined as the composite of failure modes with less than five occurrences.

7.5.2 Foreign Object Damage (FOD). Although FOD constitute the primary problem, the 3-M data has several subsidiary codes which can be combined to indicate self-induced failure and failure due to factors external (foreign to the power plant. Because in practice it is virtually impossible to distinguish accurately between the two, all FOD data are

shown here as combined. Thus, the data in this subsection shows FOD to have been the major cause of the engine removals, with 80 (33 percent) of the 240 documented failures broken down by engine type as follows:

<u>ENGINE</u>	<u>FODs</u>
J-52	24
J-79	29
T-56	4
T-48	13
TF-30	4
TF-41	<u>6</u>
Total	80

Interviews with flight and AIMD personnel verified that FOD constitutes the major failure area, particularly in the J-52 and J-79 communities.

7.5.3 Thermal Stress. Excessive thermal stress can arise from a number of causes, including improper trim and pilot problems whereby the engine operates at elevated temperatures. The resulting stress causes damage to the hot section and load-carrying structures and components within an engine. Malfunction codes indicative of thermal stress leading to engine failure include those for cracks, overheating, incorrect temperature readings in the aircraft, and disregard of over-temperature indications. On the basis of failure data and interviews, all temperature - related engine failures considered in this study have been combined under the general mode of thermal stress. Accordingly, the documentation shows that 73 (30.42 percent) of the 240 engines studied failed due to thermal stress, as follows:

<u>ENGINE</u>	<u>THERMAL STRESS</u>
J-52	1
J-79	28
T-56	3
T-58	3
TF-30	9
TF-41	<u>29</u>
Total	73

Thermal stress, therefore, looms as the second principal cause of engine failure.

7.5.4 Oil Leakage and Excessive Vibration. Internal leakage of lubricating oil and excessive engine vibration appear as two relatively minor problem areas. The studied data show that such leakage occurred

in 22 (9.2 percent) of the 240 engine failures, with excessive vibration accounting for only 10 (4.2 percent) of the total. The following lists these failures by engine type and mode:

<u>ENGINE</u>	<u>OIL LEAKAGE</u>	<u>EXCESSIVE VIBRATION</u>
J-52	7	2
J-79	5	
T-56	1	2
T-58	4	2
TF-30	3	
TF-41	<u>2</u>	<u>4</u>
Total	22	10

7.6 Failure Causal Factors.

7.6.1 General. Although the MDCS documentation contains a measure of failure mode data, the actual causal factors in the documented failures are not specifically delineated in the reporting systems. This means that a hypothetical or inferred set of causal factors based upon cause-and-effect relationships must be established. Thus, by considering effect as equal to a failure mode, probable cause of engine failure can be reasonably assumed. For example, it has been shown that FOD constitutes a principal failure mode. Assume, then, that a relationship between an operating environment, airframe design, power plant accessibility, and maintenance personnel skill and experience can be established. It can then be stated that these elements contribute in varying degree to FOD. This methodology established the following unweighted causal factors for the previously documented engine failures:

- . a. Operational Environment.
- b. Airframe design and power plant accessibility.
- c. Power plant rating as imposed by mission requirements.
- d. Faulty, inadequate, or improperly interpreted sensors and instrumentation.
- e. Levels of maintenance personnel skill and experience.

The above causal factors are discussed in detail in the following subsections.

7.6.2 Operational Environment. The effect of the operational environment on Navy Aircraft engines is twofold. In the first place, the performance envelope requirement, with respect to power plant internals

are severe. For example, the aircraft engine must function for a high percentage of time at maximum power levels, be subject to frequent high "g" loadings, sustain frequent thermal cycling and frequent and abrupt shifts in power output. Secondly, external to the engine the CVA (Attack Carrier) environment in which the engine must function is inducive to FOD. Multiple take-offs and landings, with their increase in ground (flight deck) operations and at high power levels, are necessarily associated with high "g" loadings in the course of training flights, maneuvering, catapult launchings and arrested landings. The operational environment is therefore one of the causal factors of FOD, thermal stress, internal leakage of oil, and excessive vibration. Such an operating environment is intrinsically severe, yet is incapable of being modified significantly without placing aircraft missions in jeopardy.

7.6.3 Airframe Design and Power Plant Accessibility. The causal factor here is threefold. First, the airframe can contribute to engine failure. For example, under high power/low velocity operating conditions the inlet ducts of the F-4J and the A-6 series aircraft are believed to generate a standing vortex at the duct lip. As a result, this vortex is apparently able to ingest sizeable objects, thus may be a cause of the relatively high FOD failures documented against the J-52 and J-79 engines.

Secondly, the present marriage of airframe and engine frequently creates unfavorable conditions for on-equipment inspections. Thus, an engine buried deep within an airframe results in restricted, indifferent or even no maintenance at all until actual failure occurs. Present inspection techniques to detect FOD customarily necessitate personnel entry into the air intake to permit examination of engine inlet guide vanes and the first stages of the compressor. Interviews have confirmed the suspicion that assorted debris is left behind from pockets, uniforms and shoes. Although one-piece suits are available for such inspections, the fact remains that they are not always worn. This generates the suspicion that the present inspection technique actually aggravates the initial problem, if not actually precipitates one.

In the third consideration, inadequate accessibility to installed engines, whether by borescope or personnel entry, may result in secondary failures because their primary cause goes undetected. In summation, airframe design with attendant power plant impaired accessibility is deemed a significant causal factor in FOD and in internal oil leakage.

7.6.4 Power Plant Rating. The performance requirements for military aircraft necessarily dictate employment of a high thrust capability engine operating within severe spatial constraints. To achieve the so-called "Military" power rating, combustor temperatures have been elevated beyond a level compatible with a long service life. The situation is aggravated by the present inability of engine temperature sensors (thermocouples) to provide accurate data to installed instru-

mentation; as will be discussed in subsection 7.6.5. The result is undetected thermal stress in the hot section of the engine and in associated load-carrying hardware. Thus, TF-41 data reveals 505 failures of combustion chamber liners and more than 1,000 failures of gas turbine sections attributable to high (Military) power plant ratings.

7.6.5 Sensors and Instrumentation. The examined data indicates that the development of engine temperature sensors and associated instrumentation has not kept pace with engine technology. The trend toward high operating temperatures with attendant more critical hot sections, coupled with increased concern with short-term temperature transients, present thermocouple sensors are inadequate. The delay in response time inhibits the precise time/temperature indication which is essential to awareness of impending engine failure due to thermal stress. The associated aircraft instrumentation and installed test equipment also lags the state of the art in its accuracy and in its calibration/qualification procedures.

For example, the JET CAL is used to check exhaust gas temperatures (EGT) indicators for possible error, employing a tolerance of $\pm 40^{\circ}\text{C}$ either in or out of the airframe. If instrument discrepancies are not detected and reported by flight crews, and if 300 hours serves as the qualification interval for JET CAL use in PM, then the instrumentation will remain in a status quo either until the next scheduled PM or until the next PAR (Progressive Aircraft Rework) at depot level. The adverse combination of sensor lag, instrumentation inaccuracy, and the high percentage of operational time at maximum power levels contribute heavily to the documented high incidence of thermal stress leading to engine failure.

Appendix J lists JETF instrumentation against typical aircraft.

7.6.6 Maintenance Personnel Skill and Experience. The continuing increase in power plant complexity and performance has not been matched by enhanced training or experience by maintenance personnel. In fact, force reductions have severely decreased the experience level, depth and quality of supervision and impaired operations due to prevalent undermanning at critical levels -- all of these in the same time-frame as engines of increased complexity appeared in the inventory. It is difficult, however, to associate specific failure modes with lack of maintenance skills except where FOD is involved, as discussed in subsection 7.6.3. The failure data given in Appendix B shows that seven engines were removed from their airframes for reasons reflected in the broad Malfunction Codes relating to improper maintenance. Five such failures were attributed to incorrect adjustments or alignments, faulty, or improper maintenance action in the case of the TF-41 engines. Although the MDCS is capable of determining and quantifying the influence of inexperience in maintaining individual engines over a multi-year interval, exploitation of such data is beyond the scope of this study.

7.7 Non-Integrated Engine Diagnostic Test Equipment.

7.7.1 Definition. For purposes of this report, non-integrated engine diagnostic test equipment:

- a. Is separate from the engine;
- b. Utilizes installed sensors, or has adapters and sensors compatible with existing engines;
- c. Does not require a major retro-fit of sensors;
- d. Is capable of acquiring and using presently available data; and
- e. Can integrate available data but cannot do the same for existing hardware.

7.7.2 Current Status. CGSE (Common Ground Support Equipment) that meets the foregoing definition of non-integrated engine diagnostic test equipment and presently assigned to the O, I and Depot levels of maintenance include the JET CAL Analyzer, TRIM TESTER, JETF and the spectrometers used in the SOAP. Based upon discussions with fleet and shore establishment users of such equipment, each can be rated in terms of effectiveness and utilization as follows:

<u>EQUIPMENT</u>	<u>EFFECTIVENESS</u>	<u>UTILIZATION</u>
JET CAL Analyzer	Adequate	Varies between engine types and squadrons.
TRIM TESTER	Inferior	Frequently mistrusted and not used at "O" level.
JETF	Adequate	Used as functional check after inspection and/or repair at "I" level.
SOAP	Adequate	Engines on program are dictated by Type Commander. Sample interval is not monitored for compliance and has wide variation.

An evaluation of the foregoing equipments is set forth in the following subsections.

7.7.3 JET CAL Analyzer. On the basis of interviews with cognizant O and I level personnel, it was determined that a properly calibrated JET CAL is an effective diagnostic tool. If, however, the obtainment of such a unit is difficult and the time is critical, there is a demonstrated tendency to skip the time-consuming hookup and checkout essential to its use in testing the aircraft instruments. This is particularly the case during the troubleshooting of reported engine malfunctions. Conversely, the JET CAL Analyzer is used extensively during scheduled maintenance action supported by a MRC (Maintenance Requirement Card). Utilization and overall effectiveness of the JET CAL Analyzer is constrained by the necessity for checkout/checkin procedures, relatively rough handling that impairs calibration and physically deteriorates the associated adapters and electrical leads, and especially by the need for expeditious TAT (Turn Around Time) of Navy aircraft.

7.7.4 TRIM TESTER. The TRIM TESTER suffers from the same line test equipment troubles as noted for the JET CAL Analyzer, plus an added calibration problem. Although the TRIM TESTER is designed to accomplish more functions than the JET CAL unit and with greater accuracy, it also goes out of calibration more frequently and easily. This has led to a pronounced lack of confidence on the part of its users such that it receives relatively low utilization. Operators confirm that despite the relatively "sanitary" environment in their test cells, the TRIM TESTER has proven unreliable.

7.7.5 JETFs. With the exception of expeditious repair, where certification of RFI status is not required, all gas turbine engines inducted for inspection and/or repair are functionally checked out via the AIMDs test cell or test stand. Interviews with test cell operators have established the adequacy of such facilities with the exception of the TF-41 installations. These latter are reported as lacking the necessary precision time/temperature measurements for the TF-41 and to require excessive time for vibration analysis. Allison, the manufacturer of the TF-41 engines, states that temperature tolerances more stringent than those the test cell can meet are required for proper testing -- a problem that has been investigated in depth via Navy correspondence. Since vibration analysis can only be accomplished via a single point hookup, the engine under test must be run up, shut down and the single point sensor relocated in another of the four available test points before testing can be continued. Tests have demonstrated that vibration in the TF-41 transits from the aft to the forward sections. The test cell operator must therefore strive to isolate the vibration section by trial and error, involving a test time of as much as eight hours. However, an equipment prototype is under development to alleviate this problem.

7.7.6 SOAP. Spectrometers are available to afloat AIMDs and shore-side NARFs. These units are capable of discriminating between twenty different metal elements entrained in engine oil. Standards set by the

Pensacola Laboratory range from Levels 1 through 5. Levels 3 through 5 are cautionary action advisories ranging from "provide an additional sample (2) at shortened intervals" to admonitions "not to fly the aircraft in question" until remedial measures become available. Trend analyses are integrated with threshold limits and advisories are issued based upon the rate of deterioration. This is achieved through manual recording of the involved engine's serial number, type and bureau number of the aircraft and organization of the sampling result in terms of its applicable elements. The result is a detailed data base for each engine thus sampled. When the sampling interval is maintained (i.e., oil changes and other disruptive events are duly reported) the SOAP can establish accurate and extremely valuable trend data.

Unfortunately, data recordings of this type are localized and their subsequent transfer from ashore to afloat and vice versa remain to be effectively established. Furthermore, research indicates a lack of effective reporting control such that the sample interval varies within engine type. Disruptive events (such as oil changes) are not always reported -- in fact, many engines, CSDs (Constant Speed Drive) and reduction gear assemblies installed in aircraft are not required to report.

The location of the labs at designated NARFs poses an additional problem that negates real-time analysis. In some instances, oil samples are mailed to the lab, thus incurring as much as ten days delay between sampling and analysis. Conversely, when the samples are local and permit carrying them to the lab, results can be reported in as little as three hours.

Some SOAP shortcomings are considered justified by fleet personnel as follows:

- a. There is difficulty in taking samples from aircraft within the time constraints and processing of the samples;
- b. There is a relatively high MTBF (Mean Time Between Failures) of certain engine types, CSDs and reduction gear assemblies;
- c. Lab locations cause a lack of real-time reporting;
- d. Prior to afloat installation of spectrometers there was a lack of program continuity; and
- e. A prior study of SOAP indicated only a 60 percent effectiveness of that effort.

7.7.7 Optical FOD Detection. FOD, which is the most prevalent engine failure mode, is probably aggravated by current inspection methods which require personnel entry into the engine intake ducts. The optical FOD

detection technique outlined below allows for visual inspection of the first stage from the intake proper and without personnel entry. In brief, an optical sighting device consisting of a terrestrial telescope and a variable time base stroboscopic light source is directed at a segment of the first compressor stage. In all cases, the intake configuration of current Naval aircraft permits line-of-sight alignment from a position at the inlet to a segment of the first compressor stage. The compressor is rotated at a sensibly constant rate in the starting mode and the light source is synchronized to the rotational frequency. By means of the telescope a magnified inspection is made and tracked through all blades.

Assuming a photographic quality lens and screen, an optical resolution equivalent to a circle of confusion 0.05 inches diameter can be expected on an image size 2½ inches diameter. Further, where ducting alignment permits the optical technique may be applied to the aft turbine rotor, afterburner and afterburner nozzles.

7.8 Diagnostic System.

7.8.1 Elements of a Diagnostic System. Having examined the current failures experienced by gas turbine engines, identified some probable causal factors, and reviewed the available diagnostic equipment, it is appropriate at this point to establish the elements of a diagnostic system as related to gas turbine engines. These elements can be described as:

1. Engine Data Output Facility
2. Sensors
3. Data Acquisition
4. Analysis/Diagnosis/Prognosis
5. System Response

and are worthy of discussion for an understanding of the non-integrated diagnostic problem.

7.8.1.1 Engine Data Output Facility. Diagnosis, the identification of mechanical or performance degradation, requires the availability of information or intelligence both generously available in a turbine engine. This information, usually gathered by a sensor and converted from physical dimension to electrical for transmission is only available in a mechanical sense by design. In current gas turbine engines, now some fifteen years behind in the design state-of-the-art, data output facilities were designed to provide limited pressure, temperature,

and rotational speed data only as a monitor and operational convenience. While the limited data output facilities in current gas turbine engines present a formidable challenge to the design of an effective diagnostic system, it does not appear to present an insurmountable obstacle.

7.8.1.2 Sensors. As with data output facilities, sensors installed in operational gas turbine engines lag the state-of-the-art by many years. Their accuracy, in many cases, is doubtful. For this reason, sensor output is considered an "indication" of a parameter rather than a measure of the absolute value of the particular parameter. While a certain degree of measurement accuracy is required, even more significant to the use of the sensor output as an input to a diagnostic system is the repeatability accuracy. Research conducted within the limited time of this effort did not discover any serious effort to measure repeatability accuracy of gas turbine sensors. If sensor output is to be utilized in a diagnostic loop, the accuracy of repeatability is of equal if not greater importance than accuracy of the measurement of the absolute value of the parameter.

7.8.1.3 Data Acquisition. By definition, the short term transient nature of turbine data is beyond real time human capture and comprehension. Utilization of this data as input to a diagnostic system requires either an onboard recording device or a time sample of data recorded under specified stable operating conditions during ground or flight operations. The data may be a measurement of selected parameters, utilizing installed sensors or maybe an acoustical signature. The types of required data is determined by the subsequent diagnostic processing system.

7.8.1.4 Analysis/Diagnosis/Prognosis. Presupposing that the data gathered by whatever means is valid, accurate, and conditioned, the processes of analysis, diagnosis, and prognosis can be considered individually. Analysis, for the purpose of this section of the report, is considered as the examination of data for form followed by evaluation or comparison against an established standard. It does not include fault identification or future likely behavior prediction. Analysis is concerned with data only and is not, at this juncture, offering an opinion by man or machine.

The comparative function is performed against two forms of data; one, characteristic, represents normal functions within limits. For example, both indices corrected for ambient and operating conditions, at a given fuel flow, temperature at entry to the first turbine stage has clearly defined upper and lower limits. That the fuel flow as a prime function is correct, is, for the immediate purpose, of no concern. The second data form for comparison is concerned with a particular engine, is particular to that unit, and is generally called trend information. Trend analysis is concerned with data comparison against previous occurrences under similar conditions all within prescribed and allowable

limits. As suggested by name, it monitors change from which prognosis can be made based on the characteristic previously defined. Analysis, therefore, examines and compares data against expected or prior performance and is concerned with engine health and behavior as data.

Diagnosis, as a first adjunct to the analysis process, is concerned with the identification and isolation of faults. A comparative process against the engine characteristic, diagnostic techniques are programmed, human or machine driven, to recognize symptoms, generally multiple, and consequential to a fault or faults. Thus, a device is required to store not only basic characteristics, but also multiple failure modes and their consequences, all based on "normal" data.

Prognosis, on the other hand, is concerned with the processed data within operational limits but exhibiting a trend with respect to time, which from program experience, indicates a progressive degradation or an excursion towards fault or failure. It is this process which, by detecting anomalies at an early stage, can demonstrate cost effectiveness by indicating maintenance action prior to off limit faults or secondary consequences.

7.8.1.5 System Response. Response to an engine diagnostic system is measured and expressed in two forms:

- a. On-board data presentation
- b. Flight line response to data input

The onus on the system by organization, control, and enforcement is to speed the collected data through a decision process and present feedback to the engine custodian concerning present health and prognostication for the future. In order to achieve this function, records applicable to a given engine unit must be retrieved, updated by trend, and retained.

In service, a diagnostic system comprised of the above mentioned elements has the capability to:

- a. Monitor the location and condition of all engines.
- b. Detect and identify faults.
- c. Trend performance and mechanical parameters to project future engine health.
- d. Project remaining service life.
- e. Project maintenance actions.

- f. Extract significant data for future generation design.
- g. Identify unusual maintenance/operation activities.
- h. Optimize engine life cycle usage.

7.9 Summary of Non-Integrated Diagnostic Problems.

7.9.1 Engine Performance. Since engine performance is determined by combustion of a measurable fuel quantity, thermodynamic conditions throughout the engine are a consequence of this fuel flow modified only by atmospheric and vehicle conditions. Therefore, fuel flow is controlled as a baseline for characteristic data to avoid "floating" conditions which cannot be corrected to accuracies within the scope of useful trend analysis.

7.9.1.2 Data Collection. Given the configuration of existing engines and airframes, only acoustical data can be collected external to the turbine/vehicle. While this acoustical data may contain information concerning certain mechanical aspects of the engine, there is apparently no technology for extracting pressure and temperature information from the acoustical data. It appears, therefore, that any non-integrated diagnostic device must be coupled to existing sensors to provide the necessary data.

7.9.1.3 Gas Turbine Condition Decision. Given that the necessary data can be extracted from a given engine, the data must be interpreted by man or machine in order to arrive at a decision concerning the condition of the engine in question. This implies a large number of personnel trained in data interpretation, a large number of machines programmed to accept and process the data, or an on-line terminal system whereby a centrally located machine processes the data from many activities. Historically, decisions of this type nature are not made solely by machine; some human monitoring of the data is inevitable. The machine may recommend but the human will decide.

7.9.1.4 System Development. Development of a cost effective non-integrated gas turbine diagnostic system is within the state-of-the art; however, it would require new support equipment, new reporting procedures, and a dedicated management program.

APPENDIX A

ENGINE CHARACTERISTICS AND
AIRCRAFT APPLICATION

MODEL NUMBER	MANUFACTURER	NO. COMPRESSOR STAGES	NO. TURBINE STAGES	TYPE	TYPE	NUMBER COMBUSTORS	MAXIMUM POWER AT SEA LEVEL	SPECIFIC FUEL CONSUMPTION AT MAXIMUM POWER	COMPRESSOR RATIO AT MAX. RPM	MAXIMUM ENVELOPE DIAMETER (INCHES)	DRY WEIGHT LESS TAILPIPE (LBS)	AIRCRAFT APPLICATION
J52-P-8A	PW	TJ	12	2	CN	9	9,300 lb.t	0.86	13.5	31	117	2,118 A-6
J79-GE-10	GE	TJ	17	3	CN	10	17,900 lb.t	1.97	13.5	39.1	208.7	3,855 F-4
T56-A-8	ALL	TP	14	4	CN	6	4,050 eShp	0.53	9.5	41	146	1,887 E-2
T56-A-14	ALL	TP	14	4	CN	6	4,910 eShp	0.50	9.5	41	146	1,885 P-3
T58-GE-10	GE	TS	10	2,1	A	1	1,400 Shp	.61	8.4	20.7	59	350 H-3
TF-30-P-408	PW	TF	16	4	CN	8	13,400 lb.t	.64	18.8	42	128	2,602 A-7
TF-41-A-2	ALL	TF	16	4	CN	10	15,000lb.t	.64	21	39.5	114.2	3,175 A-7

LEGEND:
 PW = PRATT WHITNEY
 GE = GENERAL ELECTRIC
 ALL= ALLISON

TJ = TURBO JET
 TP = TURBO PROP
 TS = TURBO SHAFT
 TF = TURBO FAN

A = ANNULAR
 CN = CANNULAR

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REVISION LIST

APPENDIX B

ENGINE MODEL	#	%	TOTAL	WHEN DISCOVERED				WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING
				FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL				
J-52	#	%	44	24 55	18 41	0	2 4		1		
J-79	#	%	89	38 43	33 37	16 18	2 2				
T-56	#	%	23	17 74	3 13	1 4	2 9	1			
T-58	#	%	37	23 62	12 32	2 6	0	1	1		
TF-30	#	%	28	10 36	18 64	0	0	1			
TF-41	#	%	69	44 64	25 36	0	0				
TOTAL	#	%	290	156 54	109 38	19 6	6 2	3 01	2		

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair)
 Activities, October 1973 through

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108.6

286

MALFUNCTION

396

406

506

696

APPENDIX C

ENGINE MODEL	#	%	TOTAL	WHEN DISCOVERED				TEST CELL	WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART
				FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE							
J-52	#	%	273	33 12	142 52	95 35	3 01	18	2				
J-79	#	%	393	87 22	136 34	165 42	5 02				26	1	1
I-56	#	%	216	104 48	52 24	35 16	25 12	20	3	1			
I-58	#	%	203	42 20	85 41	60 29	16 07	8	1				
TF-30	#	%	139	25 18	96 69	17 12	1 01	2	1	1			2
TF-41	#	%	2541	66 03	226 09	2201 86	48 02	520		14			
TOTAL	#	%	3765	357 09	737 20	2573 68	98 03	568 15	7	42 01	1	1	3

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair)
 Activities, October 1973 through March 1974.

CIRCUIT NUMBER		BROKEN	IMPROPER HANDLING	MISSING PART	LOOSE/DAMAGED HARDWARE	DETERIORATED	ADJUSTMENT IMPROPER	BINDING/STUCK/JAMMED	CHATTERING	CORRODED	FUEL FLOW INCORRECT	COMPRESSION LOW	CRACKED	DIRTY	FAILED TO OPERATE - REASON UNKNOWN	IMPROPER MAINTENANCE	FUEL NOZZLE Clogging
26	1	1			1			1	1	1	3	1	114		8		
1					5		2					36	3	55			
1		2	1			1	1			5		11	1	82	1	14	
14			1		26	1			3			95		7			
42 01	1	3	2	6	27 01	4	1	11	28 01	20		1212		19	102		

206

MALFUNCTION

396

FLUID MECHANICAL FAILURE												
1	10	LEAKING			MAINT. DUE TO "LOST IN FLIGHT" OCCURRENCE							
5	17				OIL CONSUMPTION EXCESSIVE							
9	1		1		NICKED							
	4	4			OVERSPEED							
	4				PRESSURE INCORRECT							
2	3		2	6		1	3	6	1	1	5	1
17	39 01	4	3	7	1	3	6	2	6	1	2	14
											4	2
											2	3

406

596

APPENDIX D

	TOTAL	WHEN DISCOVERED				WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART
		FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL					
J-52 ENGINE AND HIGH FAILURE COMPONENTS										
Engine	44	24	18	0	2			1		
Compressor Section										
Compressor Inlet Case	7			7			2			
Front Compressor Rotor	23		1	23						
No. 2/3 Bearing Housing	6			5			4			
Rear Compressor Rotor	18			18						
Combustion Section	28		20	8						
Combustion Outer Case	8		4	3		1	1			
Combustion Chamber	80		70	10						
Turbine Section										
Turbine Nozzle Outer Case	9		4	5			6			
RR Comp DR Turbine Rotor	5		2	3						
Main Fuel System										
Fuel Control	16	10	3	3				1		
Fuel Nozzle Support	21	1	16	4			1			
Air System										
Anti-Ice Air Valve	8	1	3	4			4			
TOTALS	273	36	141	93	3	18	2			
PERCENTAGES		13	52	34	01	7	1			

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair)
Activities October 1973 through March 1974

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1086

BROKEN																		
	IMPROPER HANDLING																	
	MISSING PART																	
		LOOSE/DAMAGED HARDWARE																
		DETERIORATED																
			ADJUSTMENT IMPROPER															
				BINDING/STUCK/ JAMMED														
					1													
						CHATTERING												
							1											
								CORRODED										
									FUEL FLOW INCORRECT									
										1								
											COMPRESSION LOW							
												CRACKED						
													1					
														DIRTY				
															FAILED TO OPERATE - REASON UNKNOWN			
																IMPROPER MAINTENANCE		
																	FUEL NOZZLE COKING	

286

MALFUNCTION

386

INTERNAL FAILURE											
1	LEAKING	Maint. due to "lost in flight" occurrence		OIL CONSUMPTION EXCESSIVE		PRESSURE INCORRECT		LOW POWER OR THRUST		UNABLE TO ADJUST	
2				NICKED						RESISTANCE INCORRECT	
7			1	OVERSPEED						SHEARED	
10							1			FAILED DUE TO MALFUNCTION OF ASSOC. EQPT.	
4			1			2				STRIPPED	
					1					2	
										VIBRATION EXCESSIVE	
										2	
										BEARING FAULTY	
										4	
										2	
										LOOSE	

4086

SUBARU		FAILED DUE TO MALFUNCTION OF ASSOC. EQPT.		STRIPPED		VIBRATION EXCESSIVE		BEARING FAULTY		LOOSE		BENT/BUCKLED/ DISTORTED		NO DEFECT		NO DEFECT - REMOVED FOR MODIFICATION		NO DEFECT - REMOVED FOR MAX. OPER. TIME		NO DEFECT - REMOVED FOR SCHED MAINT		NO DEFECT - REMOVED AS PART OF MATCHED SYS		OVERHEATED		INDICATED BY OIL ANALYSIS PROGRAM		ENG MONITOR SYS INDICATES INVESTIGATION		ENG MONITOR SYS INDICATES OVERTEMP	
2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1	2	1		
4	7	3	1	6	2	3	1	6	2	3	1	6	2	3	1	6	2	3	1	6	2	3	1	6	2	3	1	6	2		
2	3	1	4	5	3	2	1	4	5	3	2	1	4	5	3	2	1	4	5	3	2	1	4	5	3	2	1	4	5		
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30		

506

NAEC-GSED- 85
PAGE D-1

FOR SCIED MAINT		ACTION TAKEN		
	NO DEFECT - REMOVED AS PART OF MATCHED SYS			
	OVERHEATED			
	INDICATED BY OIL ANALYSIS PROGRAM			
	ENG MONITOR SYS INDICATES INVESTIGATION			
	ENG MONITOR SYS INDICATES OVERTEMP			
	SCORED/SCRATCHED			
		NO DEFECT	REPAIRED	BEYOND CAPABILITY OF MAINTENANCE
		1	36	7
			6	1
			1	22
			1	5
			18	18
4			19	9
			2	6
			53	27
			1	8
1				5
				16
				21
1			2	6
6				
2			1	121
				151
			45	55

686

APPENDIX E

	TOTAL	WHEN DISCOVERED				WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART
		FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL					
J-79 ENGINE AND HIGH FAILURE COMPONENTS										
Engine	89	38	33	16	2					
Compressor Section	5			5						
Compressor Rotor	24	1		23						
Compressor Rear Frame/ Diffuser	9			9						
Combustion Section										
Combustion Liner/Chamber	84	4	36	44						
Transition Duct	18		11	7						
Turbine Section										
First Stage Turbine Nozzle	11		4	6	1					
Second Stage Turbine Nozzle	17		6	11						
Turbine Stator Case	9	2	4	3						
Turbine Frame	13		3	10						
Exhaust Section										
Afterburner Flame Holder	5		1	4						
Forward Exhaust Duct	24	12	9	3						
Afterburner Tailpipe	35	10	15	9	1					
Main Fuel System										
Main Fuel Nozzle	10	1	1	8						
Nozzle Area Control	7	5	2							
Main Fuel Manifold	11	7	4							
Afterburner Fuel Section										
Afterburner Pressure Fuel Valve	7	3		4						
Lubrication System										
Oil Tank	10	2	5	3						
Bleed Air System	5	2	2		1					
TOTALS	393	87	136	165	5					
PERCENTAGES		22	34	42	02					

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair)
Activities, October 1973 through March 1974.

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295

MALFUNCTION

395

ITEM	DESCRIPTION	NUMBER
	MAINT. DUE TO "LOST IN FLIGHT" OCCURRENCE	
	OIL CONSUMPTION EXCESSIVE	
1	NICKED	
	OVERSPEED	
	PRESSURE INCORRECT	
	LOW POWER OR THRUST	
	UNABLE TO ADJUST	
	RESISTANCE INCORRECT	
	SHEARED	
	FAILED DUE TO MALFUNCTION OF ASSOC. EQPT.	
	STRIPPED	
	VIBRATION EXCESSIVE	
	BEARING FAULTY	
	LOOSE	
	BENT / BUCKLED / DISTORTED	
1		1
1		1
2		2
1		1
1		1
2		2
1		1
9		9
02		02

485

APPENDIX F

	TOTAL	WHEN DISCOVERED				WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART
		FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL					
T-56 ENGINE AND HIGH FAILSAFE COMPONENTS										
Engine	23	17	3	1	2	1				
Combustion Section Combustion Liner	52		6	24	22	6				
Turbine Section Turbine Unit	13 16	6 5	5 9	2 2		2 2				
Reduction Gear Section Reduction Gear/Access Door Section Reduction Gear	8 6	4 2	4			3 1				
Main Fuel System Fuel Control Fuel Spray Nozzle	18 22	13 11	5 9			1	3			
Lubrication System Main Oil Pressure/Scavenge Pump	5	3	2							
Electrical System Electronic Control Temp. Amplifier Speed Sensing Control	33	25	7	1						
Speed Sensing Control	8	6	2					1		
Bleed Air System Anti-Ice Air Valve	12	12				4				
TOTALS	216	104	52	35	25	20	3	1		
PERCENTAGES		48	24	16	12	09				

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair) Activities, October 1973 through March 1974.

1	WORN	FLUCTUATES - INSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART	LOOSE/DAMAGED HARDWARE	DETERIORATED	ADJUSTMENT IMPROPER	BINDING/STUCK/ JAMMED	CHATTERING	CORRODED	FUEL FLOW INCORRECT	COMPRESSION LOW	CRACKED	DIRTY	FAILED TO OPERATE - REASON UNKNOWN
6																
2																
2																
3																
1																
1	3															1
1																14
1									1							9
4							4									24
1								1								6
4									1							
0	3	1							2							55
9							02									25

206

MALFUNCTION

306

ION

		METAL ON MAGNETIC PLUG											
		INTERNAL FAILURE											
		1	LEAKING										
			MAINT. DUE TO "LOST IN FLIGHT" OCCURRENCE										
				OIL CONSUMPTION EXCESSIVE									
				1	NICKED								
					OVERSPEED								
						PRESSURE INCORRECT							
						1	2	LOW POWER OR THRUST					
								UNABLE TO ADJUST					
									RESISTANCE INCORRECT				
									1	SHEARED			
										2	FAILED DUE TO MALFUNC- TION OF ASSOC. EQPT.		
											STRIPPED		
											2	VIBRATION EXCESSIVE	
												BEARING FAULTY	
2	5	1	1	1	1	1	1	1	1	1	1	1	1
1	9	1	1	1	1	1	1	1	1	1	1	1	1
04													

4086

596

NAEC-GSED-85
PAGE F-1

686

APPENDIX G

		WHEN DISCOVERED						MISSING PART	
		TOTAL	FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL	WORN	FLUCTUATES - UNSTABLE	BROKEN
T-58 ENGINE AND HIGH FAILURE COMPONENTS									
Engine	37	23	12	2			1	1	
Combustion Section									
Combustion Liner	22		10	12					
First Stage Turbine Nozzle	11		9	2			5		
Turbine Section									
Gas Generator Turbine Rotor	6	1	3	2					
Power Turbine Section	6	1	2	3					
Power Turbine Right Angle Drive	12	1	7	4					
Main Fuel System									
Fuel Pump	6	2	1	2	1				
Main Fuel Control	26	5	5	12	4				
Pilot Valve	8	2	3	2	1				
Centrifugal Purifier	15	2	9	4					
Fuel Manifold Assembly	31		15	8	8				
Flow Divider	11	3	2	5	1	1			
Lubrication System									
Lube/Scavenge Pump	7		4	2	1				
Bleed Air System									
Starting Bleed Air Valve	5	2	3				1		
TOTALS	203	42	85	60	16	8	1		
PERCENTAGES		20	41	29	07	04			

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair) Activities, October 1973 through March 1974.

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286

MALFUNCTION

386

MALFUNCTION

			SLOW ACCELERATION
		1	TEMP INCORRECT
			METAL ON MAGNETIC PLUG
			INTERNAL FAILURE
		4	LEAKING
		2	MAINT. DUE TO "LOST IN FLIGHT" OCCURRENCE
			OIL CONSUMPTION EXCESSIVE
			NICKED
			OVERSPEED
		1	PRESSURE INCORRECT
		4	HIGH POWER OR THRUST
		02	UNABLE TO ADJUST
		02	RESISTANCE INCORRECT
			SHEARED
			FAILED DUE TO MALFUNCTION OF ASSOC. EQPT.
			STRIPPED

486

586

							ACTION TAKEN								
		BENT/BUCKLED/ DISTORTED	NO DEFECT	NO DEFECT - REMOVED FOR IDENTIFICATION	NO DEFECT - REMOVED FOR MFR. OPER. TIME	NO DEFECT - REMOVED FOR SCHED MAINT.	NO DEFECT - REMOVED AS PART OF MATCHED SYS	OVERTHEATED	INDICATED BY OIL ANALYSIS FEGGRAM	ENG MONITOR SYS IN- DIQUATES INVESTIGATION	ENG MONITOR SYS INDICATES MAINTENANCE	NO DEFECT	REPAIRED	REMOVED CAPABILITY OF MAINTENANCE	
1	1	1	1	4								1	19	17	
1	1	1	1	3	11									22	11
1	1	2	3	3	2	4	1							6	6
1	1	1	1											12	
1	1	2	2	31	1			3		1		1	1	7	4
4	2	2	2	15						1		2	21		
2											01	11			

696

APPENDIX H

	TOTAL	WHEN DISCOVERED					WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART
		FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL						
TF-30 ENGINE AND HIGH FAILURE COMPONENTS											
Engine	28	10	18				1				2
Combustion Section											
Combustion Chamber	79	6	69	4							
Combustion Chamber Duct	6		3	3							
Turbine Section											
Rear Compressor Drive	8		4	4			1				
Turbine Rotor											
Main Fuel System											
Main Fuel Control	10	9				1		1	,1		
Electrical System											
Turbine Outlet Thermo-couple Probe	8		2	6							
TOTALS	139	25	96	17	1	2	1	1			2
PERCENTAGES		18	69	12	01	01					01

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair) Activities, October 1973 through March 1974.

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296

MALFUNCTION

COMPRESSION LOW		MALFUNCTION									
	CRACKED	DIRTY	FAILED TO OPERATE - REASON UNKNOWN	IMPROPER MAINTENANCE	FUEL NOZZLE COKING	SPRAY PATTERN DEFECTIVE	LOW OUTPUT	FOD - UNDETERMINED	FOD - MATERIAL	FOD - BIRD	FOD - SELF
8					1			1	1	1	
79 6											CONTAMINATION
2											SLOW ACCELERATION
		7			2						TEMP INCORRECT
95		7			1	2	1	1	1	1	
68		05			01						1
											1

3086

MALFUNCTION

CONTAMINATION	SLOW ACCELERATION	TEMP INCORRECT	METAL ON MAGNETIC PLUG	INTERNAL FAILURE	LEAKING	MAINT. DUE TO "LOST IN FLIGHT" OCCURRENCE	OIL CONSUMPTION EXCESSIVE	NICKED	OVERSPEED	PRESSURE INCORRECT	LOW POWER OR THRUST	UNABLE TO ADJUST	RESISTANCE INCORRECT	SHEARED	FAILED DUE TO MALFUNC-TION OF ASSOC. EQPT.
1		1													
	1		1												
				4											
				03											
				1											
				04											
				6											

4086

04	6	RESISTANCE INCORRECT.	SHEARED	FAILED DUE TO Malfunc- TION OF ASSOC. EQPT.	STRIPPED	VIBRATION EXCESSIVE	BEARING FAULTY	LOOSE	BENT/BUCKLED / DISTORTED	NO DEFECT	NO DEFECT - REMOVED FOR MODIFICATION
										1	1
										2	3
										1	NO DEFECT - REMOVED FOR SCHED MAINT
										1	NO DEFECT - REMOVED AS PART OF MATCHED SYS
										1	OVERHEATED
											INDICATED BY OIL ANALYSIS PROGRAM
											FMC MONITOR SYS IN-

586

696

APPENDIX I

	TOTAL	WHEN DISCOVERED				WORN	FLUCTUATES - UNSTABLE	BROKEN	IMPROPER HANDLING	MISSING PART
		FLIGHT CREW	INSPECTIONS	DURING MAINTENANCE	TEST CELL					
TF-41 ENGINE AND HIGH FAILURE COMPONENTS										
Engine	69	44	25							
Compressor Section										
Low Press. Compressor Air Inlet Extension	5	1	2	2		1				
Main Low/Intermediate Pressure Rotor Vane Assy.	5		1	2	2					
High Pressure Comp. Rotor	5			5						
High Pressure Compressor Diffusery Bearing Hsg.	6			6		5		1		
Combustion Section										
Combustion Liner/Nozzle Assy.	505	1	1	503				2		
Turbine Section										
High Pressure Turbine Bearing Support Assy.	27			25	2	16				
First Stage High Pressure Turbine Vane Assy.	646		4	617	25	20				
High Pressure Turbine Rotor/Shft Assy.	496			496		471		1		
Turbine Vane Case Assy.	103			103		2		7		
Low Pressure Turbine Rotor	8		1	7				1		
Turbine Exhaust Case Assy.	253		12	241		1				
Main Fuel System										
Low Pressure Fuel Filter	5		1	4		4		1		
Main Fuel Control	16	8	3	3	2			1		
Fuel Spray Elbow	169	1		162	6					
Lubrication System										
Oil Filter	214	8	175	22	9					
Electrical System										
Temperature Limiter Amp.	9	3	1	3	2					
TOTALS	2541	66	226	2201	48	520		14		
PERCENTAGES		03	09	86	02	21				

SOURCE: Aviation 3-M Data from CER (Complete Engine Repair)
Activities, October 1973 through March 1974.

296

MALFUNCTION

396

FUNCTION

		LINE INCORRECT													
		2	1	2	1	2	1	2	1	2	1	2	1	2	
		METAL ON MAGNETIC PLUG	INTERNAL FAILURE	LEAKING	MAINT. DUE TO "LOST IN FLIGHT" OCCURRENCE	OIL CONSUMPTION EXCESSIVE	NICKED	OVERSPEED	PRESSURE INCORRECT	LOW POWER OR THRUST	UNABLE TO ADJUST	RESISTANCE INCORRECT	SHEARED	FAILED DUE TO MALFUNCTION OF ASSOC. EQPT.	STRIPPED
		2	1	2	1	2	1	2	1	2	1	2	1	2	1
		1	1	1	1	1	1	1	1	1	1	1	1	1	1
		1	1	1	1	1	1	1	1	1	1	1	1	1	1
		2	2	3	2	6	3	1	3	1	1	1	1	1	5
		2	2	3	2	6	3	1	3	1	1	1	1	1	5

486

586

FOR MAX. OPER. TIME						ACTION TAKEN		
	NO DEFECT - REMOVED FOR SCHED. MAINT	NO DEFECT - REMOVED AS PART OF MATCHED SYS	OVERHEATED	INDICATED BY OIL ANALYSIS PROGRAM	ENG MONITOR SYS INDICATES INVESTIGATION	ENG MONITOR SYS INDICATES OVERTEMP	SCORED/SCRATCHED	
2	1	1					5	45
80								19
2								4
								5
								4
								6
							463	42
								27
							4	642
								496
								103
								8
								5
							248	
								214
								9
84	1	1	1	1	1	5	976	1560
03						0	39	61

6076

APPENDIX J

TYPICAL AIRCRAFT AND TEST CELL INSTRUMENTATION		FUEL INLET TEMPERATURE	OIL INLET TEMPERATURE	COMPRESSOR INLET TEMPERATURE	OIL SCAVENGE TEMPERATURE	EXHAUST AIR TEMPERATURE	TURBINE INLET TEMPERATURE	COMPRESSOR OUTLET TEMPERATURE	OIL BREATHER PRESSURE	BLEED ANNULUS STATIC PRESSURE
J-52	AIRCRAFT					H				
	TEST CELL		X	X					X	
J-79	AIRCRAFT									
	TEST CELL		X	X					X	
T-56	AIRCRAFT	X					X			
	TEST CELL	X	X				X		X	
T-58	AIRCRAFT	X					X			
	TEST CELL	X	X	X			X			
TF-30	AIRCRAFT						X			
	TEST CELL	X	X	X		H	X	X	X	X
TF-41	AIRCRAFT					H				
	TEST CELL	X	X	X		H	X	X		

293.

